

Reducing Chemical Inputs in Vegetable Production Systems Using Crop Diversification Strategies

By Shane Broad

B. Agric. Sci. (Hons.)

**Submitted in fulfilment of the requirements for the degree of Doctor of
Philosophy**

University of Tasmania

**School of Agricultural Science and the Tasmanian Institute of Agricultural
Research**

May 2007

Authority of access

This thesis may be made available for loan and limited copying in accordance with the
Copyright Act 1968.

Declaration of originality

This thesis reports the original work of the author, except where due acknowledgement is given, and has not been submitted previously at this or any other University.

Shane Thomas Broad

Abstract

Vegetable cropping systems are becoming larger, more specialised and increasingly reliant on agro-chemicals to manage pests, diseases and weeds. These trends in vegetable production have resulted in increased efficiencies and allowed producers to maintain profitability in a marketplace with greater competition and declining gross margins. However, concern is growing among consumers about the impacts of chemicals on human health and the environment. This research program explores the benefits and costs of alternative vegetable production systems with increased plant species diversity and their potential to reduce chemical inputs.

The first trial conducted in this study focused on strip cropping with the view of adding additional layers of diversity in subsequent experiments. The trial used large plots with mixtures and monocultures of three vegetables: onions (*Allium cepa*), broccoli (*Brassica oleracea* var. *italica*) and potatoes (*Solanum tuberosum*). These vegetables were chosen to maximise diversity as they all have very different harvested products and do not share any major pests or diseases. This initial trial found that most vegetable diseases were too virulent to control with diversity alone and that onions were very poor competitors and hence not suited to mixed cropping systems. Furthermore, production benefits were found to occur at the zone of interaction, meaning that smaller plots with increased replication could be used in subsequent experiments. There were also trends indicating that the insect pest of broccoli *Plutella xylostella* was restricted by the mixed cropping system.

A cover crop of cereal rye (*Secale cereale*) was chosen as an additional layer of diversity in the second trial conducted in 04/05, due its ability to be easily killed and rolled to form a thick mat of plant material for suppressing weeds. Results from this experiment found that the numbers of *P. xylostella* and the aphid *Brevicoryne brassicae* in broccoli were significantly reduced by the cover crop but not by the broccoli/potato strip crop. Another pest of broccoli, *Pieris rapae*, was not affected by either treatment. The experiments also showed that there were no significant differences in yield or quality of both potatoes or

broccoli, in spite of the fact that broccoli grown in a cover crop matured one week later than broccoli grown in conventionally prepared soil (i.e. a bare soil background).

Experiments in 05/06 showed that reductions in the numbers of *P. xylostella* and *B. brassicae* in broccoli grown in the cover crop were primarily due to interference with host location and not predation or reduced host plant attractiveness. The reductions in *P. xylostella* numbers are of particular significance to Brassica producers as this insect has the proven ability to become resistant to every known insecticide, therefore any non-chemical control method could result in substantial reductions in insecticide use and insecticide resistance. However, *P. rapae* was not affected by the rye cover crop presumably due to superior host location ability and egg spreading behaviour. These results were supported by data from a semi-commercial trial.

In contrast to the previous years results, rye cover crop was shown to have significant effects on broccoli growth, reducing the number of leaves, plant biomass and yield as well as again delaying harvest by approximately one week. However, the rye cover crop improved the quality parameters, reduced the severity of hollow stem, eliminated excessive branching and removed the need for mechanical weeding.

An economic analysis based on the experimental outcomes of this thesis indicated that using the rye cover crop in a broccoli production system reduced the total variable costs by \$323/ha (6.7%) but also reduced the gross margin by \$151/ha (5.9%) when compared to conventional practice. However, only a 2% increase in yield, or a 7% price premium due to the reduced chemical use, would be required to eliminate this deficit.

The study also showed that mechanical challenges stemming from increasing plant species diversity in existing vegetable cropping systems, could be readily overcome through the modification of existing, commercially available farm machinery/equipment.

In summary, introducing plant species diversity into the conventional vegetable cropping system, in the form of a cover crop, showed considerable benefits to broccoli production in

terms of reduced insect pest pressure and quality improvements. Strip cropping as a diversification strategy did not result in increased yields or quality and had no significant effect on insect behaviour in the crops studied. Furthermore, this approach would be more difficult to implement commercially than the rye cover crop due to increased management complexity and incompatibility of chemical weed management strategies. Therefore future research efforts should focus on increasing plant species diversity in the vertical plane (above and below) using cover crops, rather than the horizontal plane (side by side) using strip cropping.

Table of Contents

ABSTRACT	IV
TABLE OF CONTENTS	VII
LIST OF TABLES	XIII
LIST OF FIGURES	XX
LIST OF FIGURES	XX
LIST OF PICTURES	XXIV
GLOSSARY OF TERMS	XXVII
ACKNOWLEDGEMENTS	XXVIII
CHAPTER 1 INTRODUCTION	1
1.1 Current trends in modern vegetable production systems	1
1.2 Steps in this research	4
CHAPTER 2 LITERATURE REVIEW	5
2.1 The problems of chemical dependence in agricultural production systems	5
2.2 Possible options for reducing chemical dependence in vegetable production systems	7
2.2.1 Transgenic crops	7
2.2.2 Integrated Pest Management	9
2.2.3 Organic production methods	9

2.2.4	Farming systems compatible with ecological principles	12
2.3	Research options – the best way forward?	13
2.4	Introducing plant species diversity into modern cropping systems	14
2.4.1	Side by side diversity – intercropping and strip cropping	15
2.4.2	Vertical diversity – cover crops and living mulches	16
2.4.3	Within crop diversity – multi-line cultivars and cultivar mixtures	18
2.4.4	Other levels of diversity	19
2.5	Conclusions and research starting point	19
CHAPTER 3	PRELIMINARY INVESTIGATIONS	21
3.1	Introduction	21
3.2	Methodology	21
3.2.1	System design	21
3.2.2	Crop selection	23
3.2.3	Experimental design	27
3.2.4	Trial establishment	28
3.2.5	Monitoring of crops for pests and diseases	29
3.2.6	Onion management and data collection	29
3.2.7	Potato management and data collection	32
3.2.8	Broccoli management and data collection	34
3.2.9	Data analysis	37
3.3	Results	39
3.3.1	Meteorological data	39
3.3.2	Onion yield and quality	40
3.3.3	Potato yield and quality	43
3.3.4	Broccoli yield	48
3.3.5	Diseases in onions	53
3.3.6	Diseases in potatoes	56

3.3.7 Diseases in broccoli	57
3.3.8 Insect pests	61
3.4 Discussion	62
3.4.1 Crop yields	62
3.4.2 Plant diseases	67
3.4.3 <i>Plutella xylostella</i> (diamondback moth) distribution in broccoli	68
3.5 Implications	69
 CHAPTER 4 THE IMPACTS OF A RYE COVER CROP AND STRIP CROPS ON INSECT PESTS OF BROCCOLI	 71
4.1 Introduction	71
4.2 Insect pests in Brassica cropping systems	71
4.3 Life histories of the major insect pests of Brassicas in Australia	72
4.3.1 <i>Plutella xylostella</i>	72
4.3.2 <i>Pieris rapae</i>	74
4.3.3 <i>Brevicoryne brassicae</i>	74
4.4 Insect pest host location	75
4.5 Methodology	78
4.5.1 Choice of the cover crop	78
4.5.2 Field trial designs	79
4.5.3 Trial establishment	84
4.5.4 In-field insect sampling 04/05	84
4.5.5 Establishing a <i>P. xylostella</i> laboratory population	85
4.5.6 Destructive sampling 05/06	86
4.5.7 Vacuum sampling for <i>P. xylostella</i> adults 05/06	88
4.5.8 <i>P. xylostella</i> egg predation experiments 05/06	88
4.5.9 Laboratory population oviposition experiment	90

4.5.10	Semi commercial cover crop experiment 05/06	91
4.5.11	Data analysis 04/05	91
4.5.12	Data analysis 05/06	92
4.6	Results	94
4.6.1	Meteorological data	95
4.6.2	<i>Plutella xylostella</i> (diamondback moth)	96
4.6.3	<i>Pieris rapae</i> (cabbage white butterfly)	111
4.6.4	<i>Brevicoryne brassicae</i> (cabbage aphid)	119
4.6.5	Semi-commercial Trial	129
4.7	Discussion	130
4.7.1	Lepidopteran pests: <i>Plutella xylostella</i> (diamondback moth) and <i>Pieris rapae</i> (cabbage white butterfly)	130
4.7.2	<i>Brevicoryne brassicae</i> (cabbage aphid)	135
4.7.3	Parasitism Rates	136
4.8	Conclusions	137
 CHAPTER 5 THE IMPACTS OF A RYE COVER CROP AND STRIP CROPS ON YIELD AND QUALITY OF POTATOES AND BROCCOLI		
		139
5.1	Introduction	139
5.2	Methodology	139
5.2.1	Potato cover crop treatment planting and management 04/05	139
5.2.2	Potato yield and quality assessment 04/05	140
5.2.3	Broccoli yield assessment 04/05	141
5.2.4	Broccoli plant sampling procedure 05/06	141
5.2.5	Broccoli yield and quality assessment 05/06	142
5.2.6	Data analysis 04/05 and 05/06	143
5.3	Results	143
5.3.1	Potato yields 04/05	143

5.3.2	Broccoli growth and development 04/05	145
5.3.3	Broccoli yield and quality 04/05	147
5.3.4	Broccoli growth and development 05/06	149
5.3.5	Broccoli yield and quality 05/06	164
5.3.6	Broccoli nutrient analysis 05/06	168
5.4	Discussion	169
5.4.1	Development, yield and quality	169
5.4.2	The effect of the cover crop on weeds	172
5.4.3	Economic implications of the rye cover crop in broccoli cropping systems	174
CHAPTER 6	PRACTICAL ASPECTS OF INCREASING CROP SPECIES DIVERSITY: CROP MANAGEMENT AND MECHANISATION	178
6.1	Development of a low drift spray unit	178
6.2	Development of the roller/transplanter	181
6.2.1	Potential improvement to the roller/transplanter	188
6.3	Conclusion	189
CHAPTER 7	GENERAL DISCUSSION	190
7.1	Pest control implications of this research	190
7.2	Financial implications of this research	191
7.3	Environmental implications of this research	191
7.4	Future research directions	194
CHAPTER 8	SUMMARY OF RESEARCH FINDINGS	197
REFERENCES		198

APPENDICES	225
Appendix A Example ANOVA models from Chapter 3	225
Appendix B Example ANOVA models from Chapter 4	226
Appendix C Example ANOVA models from Chapter 5	226

List of Tables

Table 3.1. Interactions in a model crop system, in a one, two or three crop system, adapted from Parkhurst and Francis (1986).....	22
Table 3.2. Differences in onions, potatoes and broccoli under typical Australian conditions, compiled from Dueter (1995); Kirkman (1995); Salvestrin (1995); Dennis (1997); Donald <i>et al.</i> (2000); Horn <i>et al.</i> (2002).....	24
Table 3.3. Australian vegetable production for 2003 (ABS 2003)	26
Table 3.4. Mean monthly meteorological data for Forthside from September to March in 03/04 with long term averages in brackets.....	39
Table 3.5. Mean weight (kg) of onion samples with various neighbouring plant configurations.....	40
Table 3.6. Mean weight (kg) of five onion size gradings (mm diameter) with various neighbouring plant configurations.	40
Table 3.7. Planned pairwise contrasts of neighbouring plant configurations and onions grown in monoculture ($df=1$).	41
Table 3.8. Planned pairwise contrasts of five different size gradings of neighbouring plant configurations and onions grown in monoculture ($df=1$). Significant results are shown in bold type.	41
Table 3.9. Mean weight of onion samples per plot (kg). Plots without a superscript letter in common are significantly different ($P=0.05$).....	42
Table 3.10. Mean weight (kg) of five onion size gradings (diameter in mm) per plot. Significant results are shown in bold type. Plots in grading columns without a superscript letter in common are significantly different ($P=0.05$).	43
Table 3.11. Mean weight (kg) of potato samples with various neighbouring plant configurations.....	43
Table 3.12. Mean weight (kg) of three potato quality categories with various neighbouring plant configurations.....	44
Table 3.13. Mean weight (kg) of potato rejection categories with various neighbouring plant configurations.....	45

Table 3.14. Planned pairwise contrasts of various neighbouring plant configurations and potatoes grown in monoculture ($df=1$).	45
Table 3.15. Planned pairwise contrasts of potato quality categories of various neighbouring plant configurations and potatoes grown in monoculture ($df=1$).	46
Table 3.16. Mean weight of the potato samples per plot (kg). Plots without a superscript letter in common are significantly different ($P=0.05$).	47
Table 3.17 Mean plot weights (kg) of three potato quality categories. Significant results are shown in bold type. Plots in category columns without a superscript letter in common are significantly different ($P=0.05$).	47
Table 3.18. Mean plot rejection rankings for harvested potatoes. Significant results are shown in bold type. Plots in category columns without a superscript letter in common are significantly different ($P=0.05$).	48
Table 3.19. Mean head weight (kg) of broccoli with various neighbouring plant configurations. Neighbouring plants without a superscript letter in common are significantly different ($P=0.05$).	49
Table 3.20. Percentage of the total broccoli harvest at each cut compared to neighbouring plant configurations. Significant results are shown in bold type. Neighbours within columns without a superscript letter in common are significantly different ($P=0.05$).	49
Table 3.21. Planned pairwise contrasts of broccoli yield and the various neighbouring plant configurations and broccoli grown in monoculture ($df=1$). Significant results are shown in bold type.	50
Table 3.22. Planned pairwise contrasts of the fraction of the total harvest at each broccoli cut from the various neighbouring plant configurations and broccoli grown in monoculture ($df=1$).	51
Table 3.23. Mean broccoli head weight per plot (kg) \pm SE. Plots without a superscript letter in common are significantly different ($P=0.05$).	52
Table 3.24. Percentage of the total broccoli harvest at each cut per plot. Significant results are shown in bold type. Plots within columns without a superscript letter in common are significantly different ($P=0.05$).	52

Table 3.25. Planned pairwise contrasts of various neighbouring plant configurations and broccoli grown in monoculture with all plots included and with the lowest yielding plots removed ($df=1$). Significant results are shown in bold type.....	53
Table 3.26. Schematic of plots and number of plants per strip with downy mildew infection (<i>P. destructor</i>). Plots without a superscript letter in common are significantly different ($P=0.05$).....	54
Table 3.27. Mean downy mildew (<i>P. destructor</i>) incidence with Plot 5 removed. Plots without a superscript letter in common are significantly different ($P=0.05$). ...	55
Table 3.28. Mean downy mildew (<i>P. destructor</i>) incidence compared to neighbouring plant configurations.....	55
Table 3.29. Planned pairwise contrasts of downy mildew (<i>P. destructor</i>) incidence and various neighbouring plant configurations and onion monoculture ($df=1$).	55
Table 3.30. Mean downy mildew (<i>P. destructor</i>) incidence compared to neighbouring plant configurations with Plot 5 results removed.....	56
Table 3.31. Planned pairwise contrasts of the average downy mildew (<i>P. destructor</i>) incidence and various neighbouring plant configurations and onion monoculture with Plot 5 data removed ($df=1$).....	56
Table 3.32. Percentage of the broccoli harvest rejected due to white blister rust (<i>A. candida</i>) compared to neighbouring plant configurations. Neighbouring plants without a superscript letter in common are significantly different ($P=0.05$).	57
Table 3.33. Neighbouring plant row comparisons of the percentage of broccoli heads rejected at each cut due to infection with white blister rust (<i>A. candida</i>). Significant results are shown in bold type. Neighbouring plants within columns without a superscript letter in common are significantly different ($P=0.05$). ...	58
Table 3.34. Planned pairwise contrasts of the percentage of harvested broccoli heads rejected due to white blister rust (<i>A. candida</i>) of various neighbouring plant configurations and broccoli monoculture ($df=1$).....	58
Table 3.35. Planned pairwise contrasts of the percentage of broccoli heads rejected at each cut due to white blister rust (<i>A. candida</i>) of various neighbouring plant configurations and broccoli monoculture ($df=1$).....	59

Table 3.36. Mean plot percentages of harvested broccoli heads rejected due to white blister rust (<i>A. candida</i>) \pm SE. Plots without a superscript letter in common are significantly different ($P=0.05$).....	60
Table 3.37. Mean plot percentages of harvested broccoli heads rejected at each cut due to infection with white blister rust (<i>A. candida</i>) \pm SE. Significant results are shown in bold type. Plots within columns without a superscript letter in common are significantly different ($P=0.05$).....	60
Table 3.38. Neighbouring plant configurations and the incidence of diamondback moth (<i>P. xylostella</i>) larvae per plant.	61
Table 3.39. Planned pairwise contrasts of the incidence of diamondback moth (<i>P. xylostella</i>) in neighbouring plant row configurations and the broccoli monoculture ($df=1$).....	62
Table 3.40. Plot yield rankings and Fishers LSD groupings of the three crops.....	63
Table 3.41. Rain gauge measurements (mm) from 11/2/04 (#1) and 17/02/04 (#2) from the locations illustrated on Figure 3.4.	64
Table 4.1. Mean monthly meteorological data for Forthside from September to March in 04/05 and 05/06 with long term averages in brackets.....	95
Table 4.2. The effect of treatment (four cropping systems) and planned comparisons of the abundance of <i>P. xylostella</i> larvae in 04/05. Significant results are shown in bold type.	97
Table 4.3. Mean number of parasitised <i>P. xylostella</i> per 20 larvae from 04/05.	98
Table 4.4. The effect of treatment (four cropping systems) and planned comparisons of the parasitism rates of <i>P. xylostella</i> fourth instar larvae collected in 04/05.....	98
Table 4.5. The effect of treatment (four cropping systems) and planned comparisons of the abundance of <i>P. xylostella</i> pupae in 04/05. Significant results are shown in bold type.	99
Table 4.6. The effect of treatment (six cropping systems) and planned comparisons of the abundance of <i>P. xylostella</i> adult moths in 05/06. Significant results are shown in bold type.....	101
Table 4.7. Average number of eggs oviposited by <i>P. xylostella</i> on leaf samples in the adult moth laboratory cage \pm SE.	102

Table 4.8. ANOVA model and planned comparisons of the number of eggs oviposited by <i>P. xylostella</i> on leaf samples in the adult moth laboratory cage in 05/06.	103
Table 4.9. The effect of treatment (six cropping systems) and planned comparisons of the abundance of <i>P. xylostella</i> eggs in 05/06. Significant results are shown in bold type.	104
Table 4.10. Mean number of <i>P. xylostella</i> eggs oviposited on plants in exclusion cages in 05/06. Treatments without a letter in common are significantly different ($P=0.05$).	105
Table 4.11. The effect of treatment (six cropping systems) and planned comparisons of the abundance of <i>P. xylostella</i> eggs oviposited on plants in exclusion cages in 05/06. Significant results are shown in bold type.	106
Table 4.12. Comparison of outcomes for <i>P. xylostella</i> eggs oviposited in the exclusion cage experiment.	107
Table 4.13. The effect of treatment (six cropping systems) and planned comparisons of the abundance of <i>P. xylostella</i> larvae in 05/06. Significant results are shown in bold type.	110
Table 4.14. The effect of treatment (four cropping systems) and planned comparisons of the abundance of <i>P. rapae</i> larvae in 04/05. Significant results are shown in bold type.	112
Table 4.15. The effect of treatment (six cropping systems) and planned comparisons of the abundance of <i>P. rapae</i> eggs in 05/06. Significant results are shown in bold type.	114
Table 4.16. The effect of treatment (six cropping systems) and planned comparisons of the abundance of <i>P. rapae</i> larvae in 05/06. Significant results are shown in bold type.	116
Table 4.17. The effect of treatment (four cropping systems) and planned comparisons of the proportion of sampled plants with <i>B. brassicae</i> colonies in 04/05. Significant results are shown in bold type.	120
Table 4.18. The effect of treatment (four cropping systems) and planned comparisons of the proportion of sampled plants with parasitised <i>B. brassicae</i> in 04/05. Significant results are shown in bold type.	122

Table 4.19. The effect of treatment (six cropping systems) and planned comparisons of the abundance of alate <i>B. brassicae</i> in 05/06. Significant results are shown in bold type.	124
Table 4.20. <i>B. brassicae</i> colonies in 05/06 logistic regression estimates with <i>P</i> values in brackets. Significant tests are shown in bold type.	126
Table 4.21. <i>B. brassicae</i> parasitism in 05/06 logistic regression estimates with <i>P</i> values in brackets. Significant tests are in bold type.	128
Table 4.22. The effect of treatment (Cover crop and Bare soil) on the abundance of insects in the semi-commercial trial at Gawler in 05/06. Significant results are shown in bold type.	130
Table 5.1. Potato treatment yields 04/05.	143
Table 5.2. The effect of treatment (four cropping systems) and planned comparisons of potato yield and quality in 04/05.	144
Table 5.3. The effect of treatment (four cropping systems) and planned comparisons of broccoli leaf area and plant biomass in 04/05. Significant results are shown in bold type.	146
Table 5.4. The effect of treatment (four cropping systems) and planned comparisons of the number of days from transplanting to harvest in 04/05. Significant results are shown in bold type.	147
Table 5.5. The effect of treatment (four cropping systems) and planned comparisons of harvested head weight per plant in 04/05. Significant results are shown in bold type.	148
Table 5.6. The effect of treatment (six cropping systems) and planned comparisons of the number of leaves per plant in 05/06. Significant results are shown in bold type.	150
Table 5.7. The effect of treatment (six cropping systems) and planned comparisons of total leaf dry weight in 05/06. Significant results are shown in bold type.	152
Table 5.8. The effect of treatment (six cropping systems) and planned comparisons of mean leaf dry weight per plant in 05/06. Significant results are shown in bold type.	154

Table 5.9. The effect of treatment (six cropping systems) and planned comparisons of stem dry weight in 05/06. Significant results are shown in bold type.....	157
Table 5.10. The effect of treatment (six cropping systems) and planned comparisons of the number of branches per plant in 05/06. Significant results are shown in bold type.....	159
Table 5.11. The effect of treatment (six cropping systems) and planned comparisons of stem length in 05/06. Significant results are shown in bold type.....	160
Table 5.12. Proportion of plants with initiated heads at 36 DAT \pm SE.	162
Table 5.13. The effect of treatment (six cropping systems) and planned comparisons of head diameter development in 05/06. Significant results are shown in bold type.	163
Table 5.14. The effect of treatment (six cropping systems) and planned comparisons of the number of days from transplanting to harvest in 05/06. Significant results are shown in bold type.	164
Table 5.15. The effect of treatment (six cropping systems) and planned comparisons of the harvested head weight per plant in 05/06. Significant results are shown in bold type.....	165
Table 5.16. The effect of treatment (six cropping systems) and planned comparisons of the branching angle score in 05/06. Significant results are shown in bold type. ...	166
Table 5.17. The effect of treatment (six cropping systems) and planned comparisons of the shape score in 05/06. Significant results are shown in bold type.....	167
Table 5.18. The effect of treatment (six cropping systems) and planned comparisons of hollow stem score in 05/06. Significant results are shown in bold type.	168
Table 5.19. The effect of treatment (six cropping systems) and planned comparisons of on the potassium content per plant in 05/06. Significant results are shown in bold type.....	169
Table 5.20. Broccoli crop enterprise budget of the Bare Soil Monoculture and the Cover Crop Monoculture Treatment harvest means and is based on current cash crop budgets (DPIW 2005).....	177
Table 7.1. Toxicity of insecticides registered for broccoli in Australia (APVMA [2006] and associated Material Safety Data Sheets)	192

List of Figures

Figure 3.1. Experimental design for 03/04.	28
Figure 3.2. Schematic of naming of a middle 4.95m potato strip cropping strip (left) and a schematic of a 4.95m potato strip cropping strip on a plot edge (right).	37
Figure 3.3. Schematic of naming of a middle 4.95m onion strip cropping strip (left) and a schematic of a 4.95m onion strip cropping strip on a plot edge (right).	39
Figure 3.4. Rain gauge locations superimposed onto the experimental design.	64
Figure 4.1. Experimental design 04/05. P=potato, B=broccoli and diagonal lines=cover crop.....	81
Figure 4.2. Experimental design 05/06. Where green=potato strips, yellow=rye strips, grey=cover crop broccoli and clear=bare soil broccoli.....	83
Figure 4.3. Sampling schematic for 05/06 experiment, where the numbers indicate a broccoli plant and the highlighted plants were “selectable”.	87
Figure 4.4. The mean number of <i>P. xylostella</i> larvae per plant sampled in 04/05 \pm SE. “ns” not significant; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).	96
Figure 4.5. The mean number of <i>P. xylostella</i> pupae per plant sampled in 04/05 \pm SE. “ns” not significant; ** $P \leq 0.01$. Points without a letter in common are significantly different ($P=0.05$).	99
Figure 4.6. <i>P. xylostella</i> vacuum sampling results with female moths from the six treatments \pm SE (left) and the male moths from the six treatments \pm SE (right). Cc-M = Cover crop/Monoculture; Cc-Ry = Cover crop/Rye strips; Cc-Po = Cover crop/Potato strips; Bs-M = Bare soil/Monoculture; Bs-Ry = Bare soil /Rye strips; Bs-Po = Bare soil /Potato strips; Male moths captured 36 DAT (blue columns on the right) without a letter in common are significantly different ($P=0.05$).	101
Figure 4.7. The mean number of <i>P. xylostella</i> eggs per plant sampled in 05/06 \pm SE. “ns” not significant; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).	104

Figure 4.8. The probabilities of the three outcomes from the cage egg survival experiment where the eggs could have been predated (Attacked), hatched (Hatched) or were missing (Missing).....	108
Figure 4.9. The mean number of <i>P. xylostella</i> larvae per plant sampled in 05/06 \pm SE. “ns” not significant; * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).....	109
Figure 4.10. <i>P. xylostella</i> populations at each 05/06 sample as eggs, 1 st , 2 nd , 3 rd and 4 th instars or pupae.....	111
Figure 4.11. The mean number of <i>P. rapae</i> larvae per plant sampled in 04/05 \pm SE. “ns” not significant; * $P \leq 0.05$. Points without a letter in common are significantly different ($P=0.05$).....	112
Figure 4.12. The mean number of <i>P. rapae</i> eggs per plant sampled in 05/06 \pm SE. “ns” indicates that there were no significant differences for that sampling date. ...	114
Figure 4.13. The mean number of <i>P. rapae</i> larvae per plant sampled in 05/06 \pm SE. “ns” not significant; * $P \leq 0.05$. Points without a letter in common are significantly different ($P=0.05$).....	116
Figure 4.14. <i>P. rapae</i> populations at each 05/06 sampling date summarised as: eggs; 1 st and 2 nd instar (small) ; 3 rd and 4 th instars (medium); 5 th instar (large); and pupae.	118
Figure 4.15. The percentage of sampled plants in 04/05 with <i>B. brassicae</i> colonies present. “ns” not significant; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).....	120
Figure 4.16. The percentage of plants sampled in 04/05 with parasitised <i>B. brassicae</i> . ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).....	122
Figure 4.17. The mean number of alate <i>B. brassicae</i> per plant sampled in 05/06. ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).....	124
Figure 4.18. The probability of <i>B. brassicae</i> presence on broccoli plants with 95% confidence intervals.....	127
Figure 4.19. Probability of <i>B. brassicae</i> parasitism with 95% confidence intervals.	129

Figure 4.20. Mean number of various insects and eggs from the semi-commercial trial at Gawler taken 23 DAT in 05 \pm SE. “ns” not significant; * $P \leq 0.05$	130
Figure 5.1. The percentage by weight of the 04/05 potato harvest allocated to each quality category \pm SE	144
Figure 5.2. Mean broccoli plant partitioning results from 04/05 \pm SE, ns” not significant; * $P \leq 0.05$; ** $P \leq 0.01$. Individual columns within each group without a letter in common are significantly different ($P=0.05$).	146
Figure 5.3. The mean number of days from transplanting to harvest in 04/05 \pm SE. Treatments without a letter in common are significantly different ($P=0.05$).	147
Figure 5.4. Broccoli mean harvested head weights in 04/05 \pm SE.	148
Figure 5.5. Total combined broccoli yields per plot in 04/05. DAT=days after transplanting.	149
Figure 5.6. Mean number of leaves of broccoli plants in 05/06 \pm SE. “ns” not significant; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).	150
Figure 5.7. The log of total leaf dry weight per plant from 05/06 \pm SE. * $P \leq 0.05$; *** $P \leq$ 0.001. Points without a letter in common are significantly different ($P=0.05$).	152
Figure 5.8. Mean leaf dry weight in 05/06 \pm SE. ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).	154
Figure 5.9. Log of mean stem dry weight 05/06 \pm SE. *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).	156
Figure 5.10. Mean number of branches arising from and including the main stem \pm SE. *** $P \leq 0.001$. Treatments in each group without a letter in common are significantly different ($P=0.05$).	158
Figure 5.11. Mean stem length of broccoli plants from 05/06 \pm SE. “ns” not significant; * P ≤ 0.05 ; ** $P \leq 0.01$; *** $P \leq 0.001$. Points without a letter in common are significantly different ($P=0.05$).	160
Figure 5.12. Mean head diameter development of broccoli plants in 05/06 \pm SE. *** $P \leq$ 0.001. Points without a letter in common are significantly different ($P=0.05$).	162

Figure 5.13. The mean number of days from transplanting to harvest in 05/06 \pm SE. Treatments without a letter in common are significantly different ($P=0.05$). 164	164
Figure 5.14. Broccoli mean harvested head weights in 05/06 \pm SE. Treatments without a letter in common are significantly different ($P=0.05$)..... 165	165
Figure 5.15. Mean branching angle score (1-5) in 05/06 \pm SE, where 1=worst branching angle (unmarketable) and 5=best branching angle (highly marketable). 166	166
Figure 5.16. Mean shape score (1-5) in 05/06 \pm SE, where 1=worst shape (unmarketable) and 5=best shape (highly marketable)..... 167	167
Figure 5.17. Mean hollow stem score (1-4) in 05/06 \pm SE, where 1=severe hollow stem and 4=no hollow stem. 168	168
Figure 5.18. Mean Potassium (K) content of nutrient sap tests in 05/06 \pm SE. Treatments without a letter in common are significantly different ($P=0.05$)..... 169	169

List of Pictures

Picture 3.1. Onions planted into three beds per strip with 8 rows of onions per bed.....	30
Picture 3.2. Onions after lifting.....	30
Picture 3.3. Onion yield sampling using a 0.5m ² quadrat.....	31
Picture 3.4. Onions bagged for yield sampling, Plot 4 (left) and Plot 1 Onion monoculture (right).....	31
Picture 3.5. Onion size scale (left to right) >70mm, 60-70mm, 50-60mm, 40-50mm and <40mm.	31
Picture 3.6. Onion grading equipment.	32
Picture 3.7. Onion harvester (left) and close up of the harvester's lifter (right).	32
Picture 3.8. Front view (left) and rear view (right) of the potato planter.....	33
Picture 3.9. Technical Officer assuring potato set regularity.....	33
Picture 3.10. Potato yield sample being marked (left) and dug with a potato fork (right). .	33
Picture 3.11. Technical officer taking potato yield samples.	34
Picture 3.12. Six row broccoli transplanter, rear view (left) front view (right).	34
Picture 3.13. The push weeder.	35
Picture 3.14. (a). Manual harvesting (cutting) of broccoli (left). (b). Harvesting broccoli into bags hung by nails on the inside of two half tonne bins (right).	36
Picture 3.15. Scale of infection of harvested broccoli heads with white blister rust (<i>Albugo candida</i>) progressing from a no infection (left) to a high infection (right) likely to lead to rejection at the factory.	36
Picture 3.16. Downy mildew (<i>P. destructor</i>) symptoms.....	54
Picture 3.17. (a). Yellowing of onions visible after the removal of neighbouring broccoli plants (left). (b). A broccoli leaf partially shading an onion plant (right).	66
Picture 3.18. Complementarity of potato and broccoli leaf canopies on a strip edge with potatoes on the left and broccoli on the right.	67
Picture 4.1. A <i>P. xylostella</i> adult moth (left), pupa and 4 th instar (middle) and three different instars (right), the middle and right pictures also illustrate “windowing” of the leaves due to larval feeding.	73
Picture 4.2. A <i>P. rapae</i> adult (left) and <i>P. rapae</i> larvae (middle) <i>P. rapae</i> chrysalid.	74

Picture 4.3. An alate <i>B. brassicae</i> adult with nymphs (left), an aphid colony with a <i>Diaeretiella rapae</i> wasp (middle), and an aphid colony with parasitised (brown) mummies (right).....	75
Picture 4.4. Treatments for the 04/05 experiment (clockwise from top left) Cover crop/Monoculture . Cover crop/Potato strips, Bare soil/Monoculture, Bare Soil/Potato strips.	82
Picture 4.5. Additional treatments for the 05/06 experiment: Bare soil/Rye strips (left) Cover crop/Rye strips (right). Note that the photos were not taken on the same day.	83
Picture 4.6. The author inspecting broccoli plants using jewellers glasses.	87
Picture 4.7. (a). Exclusion cage with netting before placement (left). (b). An uncovered cage surrounding a broccoli plant (right).	90
Picture 4.8. Placing moths in exclusion cages, with the moth containers and equipment (left) and re-sealing the entrance hole (right).....	90
Picture 4.9. <i>P. rapae</i> pupating on an onion plant.....	119
Picture 5.1. Potato Cover crop/Monoculture after planting 04/05.	140
Picture 5.2. Digging (left) and bagging (right) potatoes from the 04/05 experiment.	140
Picture 5.3. A plant marked for harvest with a white stick.	142
Picture 5.4. Head shape – convex (5) to concave (1) (left) and branching angle tight (5) to spreading (1) (right) scales from (Tan <i>et al.</i> 1999).	142
Picture 5.5. Broccoli hollow stem scale with rankings in brackets (from left) – no hollow stem (4), trace (3), minor (2) and severe (1).	143
Picture 5.6. An unweeded area between two plots in 05/06 experiment	172
Picture 5.7. Infestation of wild radish in the 04/05 experiment controlled by the rye cover crop on the right, with the interplot region marked with a black line. Note that the plot pictured in Picture 5.8 is in the background.....	173
Picture 5.8. Infestation of wild radish in a bare soil plot in the 04/05 experiment, with the interplot area marked with a black line.	174
Picture 5.9. Control of wild radish by the unweeded cover crop at 48 DAP in the 04/05 experiment.....	174
Picture 6.1. (a). Side view of a Turbo Teejet® (left). (b). Assembling the sprayer (right).	179

Picture 6.2. (a). Sprayer end guard in profile with pop rivets indicated by the arrow (left). (b). The end guard attachment (right).	180
Picture 6.3. The end guard between two crops.	180
Picture 6.4. (a). Sprayer rear view (left). (b). The sprayer front view (right).	181
Picture 6.5. Cover crop in the 04/05 experiment prior to desiccation and rolling.	182
Picture 6.6. (a). The heavy roller with two trailing discs (left). (b). A demonstration of the angle iron flattener (right).	182
Picture 6.7. (a). Pre-drilling fertiliser into a flattened cover crop (left). (b). Hand planting broccoli plants (right).	183
Picture 6.8. (a). Roller construction with the drum and angle iron “crimpers” indicated by the arrow (left). (b). Attaching the roller to the tractor tool bar (right).	184
Picture 6.9. (a). The roller with the fertiliser box attached indicated by the arrow (left). (b). A cup planter unit indicated by the arrow (right).	184
Picture 6.10. (a). The double disc openers (indicated by the arrow) attached to the cup planter (left). (b). The trash guard (indicated by the arrow) attached to the double disc unit (right).	185
Picture 6.11. The prototype roller/transplanter ready for testing	186
Picture 6.12. The prototype roller/transplanter being tested in the semi-commercial trial in 05/06.	186
Picture 6.13. (a). The second prototype roller with slot maker (left). (b). A close up of the slot makers (right).	187
Picture 6.14. (a). The second prototype ready for testing (left). (b). The fertiliser box drive system attached to the roller (indicated by the arrow) (right).	187
Picture 6.15. The end result of the second prototype roller/transplanter, a rolled cover crop and transplanted broccoli (Cover crop/Rye strips Treatment).	188

Glossary of Terms

Strip crops – growing two or more crops in tractor width repetitions.

Cover crops – plants grown for ground cover that are killed prior to planting a commercial crop.

Bare soil – soil without ground cover that has been cultivated to a fine tilth.

Oviposition – the process of an insect depositing an egg.

DAT – number of days after a seedling has been transplanted.

Host location – the process an insect undertakes when attempting to find a suitable host plant.

Cosmopolitan insect – an insect that is found wherever its host plant is cultivated.

Instar – a post embryonic insect growth stage between moults.

Alatae – winged female aphids.

Apteratae – wingless female aphids.

Degenerate – having lost highly developed functions, characteristics or structures through evolution.

Gravid – carrying developing young or eggs.

Acknowledgements

This research was made possible by a number of individuals and an Australian Postgraduate Award scholarship from the University of Tasmania. Further provision of financial support in the form of a scholarship “top-up” and operating funds from Professor Rob Clark and TIAR is gratefully acknowledged. It is very unusual for a postgraduate student to be given as much latitude to research a topic of his or her own choosing, and I am truly thankful for the opportunity I was afforded.

I would like to acknowledge the in-kind contributions of the Tasmanian Department of Primary Industries and Water, Harvest Moon, Simplot and Field Fresh. Thanks go to Peter Aird from Serve-Ag for his advice on chemical treatments and his general support for my overarching research goals. Thanks are due to the staff at Forthside Research and Development Station.

My supervisors Dr. Shaun Lisson and Dr. Neville Mendham deserve thanks as they provided valuable guidance for this project and significant editorial effort. Dr. Nancy Schellhorn was an invaluable resource in helping design and analyse my final years trials. I thank Dr. David Ratkowski and Dr. Ross Corkrey for statistical advice and Dr. Nancy Endersby for kick starting my laboratory *Plutella* population.

A special commendation must go to my father Ian Broad for his significant contribution to this thesis in the way of advice, acting as a sounding board, assistance in harvesting broccoli, the provision of land for my semi-commercial trial and finally allowing me free reign of his shed, equipment and junk pile for the building of the roller/transplanter. Without his help I doubt this thesis would have happened.

Last, but not least, I would like to thank my partner Alicia for her help establishing trials and for being willing to move with me to Forth, making the long hours of trial work possible (and bearable).

Chapter 1 Introduction

This thesis began as a personal concern rather than an immediate industry based problem. This concern started to develop as I grew up on my parent's mixed crop and livestock property, on the northwest coast of Tasmania, and continued to develop as I worked as a contract vegetable grower before attending University and completing my degree in Agricultural Science. During these years, vegetable production systems increased in scale, and in the process become more reliant on agrochemicals to control competing organisms. My developing apprehension was that agriculture was becoming too reliant on chemicals inputs, which had the potential to increase problems in the future and was perhaps not the best way forward for the industry. These points initiated the question, "Are there any feasible alternatives?" This question forms the starting point of this thesis. However, before beginning to explore this question, the reasons for the current trends in vegetable production systems need to be understood.

1.1 Current trends in modern vegetable production systems

Since the geographical expansion of agriculture slowed markedly in the 1950's, crop yield increases accelerated, more than keeping pace with population growth. This resulted in a worldwide oversupply of food (Swaminathan 2004). Globalisation in agriculture and the continued breakdown of trade barriers enlarged the market available to Australian farmers but also increased the number of competitors (Barr 2004). Both oversupply and globalisation have meant continued downward pressure on agricultural product prices and declining margins between real farm receipts and real farm costs (Laurence 2000). This has led to worldwide structural changes in agriculture over the last four decades characterised by increased mechanisation, intensification of production, increasing use of external inputs and the separation of livestock and crop production (Knickel 1990).

On average, over the last 15 years, agricultural output in the Organisation for Economic Co-operation and Development (OECD) countries has increased by 15%, on 1% less land with 8% fewer workers. At the same time the inflation adjusted price of food has fallen by approximately 1% per annum (Legg and Viatte 2001). To remain globally competitive

Australian farms have become larger, more capital intensive and fewer in number (Garnaut and Lim-Applegate 1998). There has also been increasing pressure to specialise rather than diversify (Stuthman 2002) as specialisation brings economies of scale though greater mechanisation, the use of hybrid germplasm and the focusing of knowledge, research and marketing (Vandermeer *et al.* 1998). Only 50 years ago vegetable producers in Australia were small, diverse, labour intensive operations on the urban fringe with few chemicals and fertilisers available. In comparison, modern vegetable producers are highly productive, large scale, increasingly specialised operations dependent on irrigation, fertiliser, agrochemicals, transport and marketing systems and found in regions where the climate, soil and water supplies are most suited to the production of specific crops (Stirzaker 1999). Access to markets and the relative prices of outputs and inputs strongly influence the selection of crop types, crop sequences and crop management (Boiffin *et al.* 2001).

While these farming systems are extremely productive and provide low-cost food (Altieri 1998; Stirzaker 1999) they also bring a variety of economic, environmental and social problems (Altieri 1998). A focus on maximising production in the short-term without consideration of the consequences on other essential components of the agro-ecosystem has led to natural resource degradation in Australia (Williams and Gascoigne 2003). The annual cost of this resource degradation, which includes salinity, acid soils, soil structural decline, erosion, irrigation salinity, reduced water quality and invasive weed control, has been estimated to be in excess of \$A 3.5 billion (Standing Committee on Environment Recreation and Arts 2001).

At the individual farm level there has also been a subsumption of the decision making process by corporations as part of the contracting process (Tonts and Black 2002). For example, in Tasmania, vegetable processing companies make most of the decisions in relation to the selection of varieties, planting and harvesting dates, irrigation schedules, chemical applications and fertiliser requirements, and usually award annual contracts less than a year in advance (Miller 1995). This compounds the imbalance between economic and environmental imperatives, as there is little opportunity for forward planning and attempts to achieve sustainability are afforded low priority (Miller 1995).

There are very few native Australian plants that are grown as crops in any capacity. Instead crops are drawn from a diverse range of geographic locations, from South America to Europe. As a result the remnant ecosystems dispersed throughout the cropping locations have a long evolutionary history distinct from that of the introduced crops (Hill 1993). Therefore most pests, predators and diseases are also exotic in their origin. The insect pest situation is further complicated as many species have the ability to migrate in large numbers on favourable winds, at times inundating biological control mechanisms (Hill 1993).

These factors, combined with modern agriculture's reduced tolerance of weeds, pests and diseases (Vandermeer *et al.* 1998), means maintaining the productivity of soils and sustaining the rural environment in the face of declining farm profitability, is seen as the single most important issue in many agricultural industries today (Laurence 2000). Furthermore, Trewavas (1999) suggests that along with abundant (and cheap) food and greater life expectancies, has come a demand from consumers for a risk free world. Since modern farming practices have been fairly or unfairly associated with chemicals and health risks, there is an increasing demand for 'clean green' chemical free food. There have also been calls for greater use of 'sustainable' production methods in Australia due to continual scrutiny of agricultural production methods by an increasingly urbanised population coupled with an agricultural lobby with waning political power (Barr 2004). These demands are increasingly being reflected in the requirements of retailers, particularly the economically powerful supermarkets in Europe (Gunningham and Sinclair 2002) and Australia.

In summary, the current trends in Australian vegetable production are that increased global supply and competition has resulted in increased farm efficiency, management simplicity, greater reliance on inputs (including agrochemicals) and increased scrutiny by a largely urban public who desire "sustainably" produced goods. Therefore, research into vegetable cropping systems that maintain efficiency and productivity, but at the same time reduce the level of chemical inputs, could result in more marketable products and be an alternative to a

continued reliance on chemical solutions. Researching strategies to reduce chemical dependence in vegetable production also aligns well with current Australian agricultural policy statements, for example Tasmania's state government policy and promotion of Tasmanian agricultural industries as being "clean and green", with low chemical usage, and a moratorium on any use of gene technology in the production of food (Anon 2003b).

1.2 Steps in this research

The search for a feasible alternative to the current trend of increased chemical dependence in vegetable production systems, initially involved discussing the problems of chemical dependence and the benefits and disadvantages of farming systems with reduced chemicals requirements. This led to the initial choice of research direction that was further developed via a review of relevant literature (Chapter 2). This in turn generated specific research questions, with preliminary field investigations commencing in the summer of 2003/2004 with the strip cropping of potatoes (*Solanum tuberosum*), broccoli (*Brassica oleracea* var. *italica*) and onions (*Allium cepa*) (Chapter 3). Initially this project was conceived as a broad look at problems and potential solutions to chemical dependence in each of these three vegetable crops. However, the results from the initial trial demonstrated that the most interesting trends were occurring in broccoli, which is a good example of an intensively produced vegetable with the associated problems of insect pest pressure, insecticide resistance, weed pressure and rapid growth. Therefore the majority of the work in the following two years concentrated on broccoli as a key part of an intensive system. The major focus of this thesis relates to the impact of cover and strip cropping on insect populations in broccoli (Chapter 4). Agronomic and economic impacts are discussed in Chapter 5 and machinery design aspects in Chapter 6. The research detailed in this thesis covers a wide range of subject matter within the field of agricultural science including agronomy, entomology and agricultural engineering. The final chapter, Chapter 7, summarises these different aspects and discusses future research directions.